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Automotive fuels from biomass via gasification

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ABSTRACT

There exists already a market of bio-automotive fuels i.e. bioethanol and biodiesel produced from food crops in many countries. From the viewpoint of economics, environment, land use, water use and chemical fertilizer use, however, there is a strong preference for the use of woody biomass and various forest/agricultural residues as the feedstock. Thus, the production of 2nd generation of bio-automotive fuels i.e. synthetic fuels such as methanol, ethanol, DME, FT-diesel, SNG and hydrogen through biomass gasification seems promising. The technology of producing synthetic fuels is well established based on fossil fuels. For biomass, however, it is fairly new and the technology is under development. Starting from the present market of the 1st generation bio-automotive fuels, this paper is trying to review the technology development of the 2nd generation bio-automotive fuels from syngas platform. The production of syngas is emphasized which suggests appropriate gasifier design for a high quality syngas production. A number of bio-automotive fuel demonstration plant will be presented, which gives the state of the art in the development of BTS (biomass to synthetic fuels) technologies. It can be concluded that the 2nd generation bio-automotive fuels are on the way to a breakthrough in the transport markets of industrial countries especially for those countries with a strong forest industry.

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1. Introduction

The possibility of producing transportation fuels from biomass and wastes has been a more and more important issue with regard to energy shortage crisis and global warming crisis. The European Parliament has approved the EU guideline to increase the share of biofuels in all transport fuels (petrol and diesel) up to 5.75% in 2010, 10% in 2020 although only 1.4% of bio-automotive fuels is, at present, produced from biomass.

Today, there already exists a market of bio-automotive fuels supported by governments in many countries; for bio-ethanol e.g. in Brazil, USA and for bio-diesel derived from vegetable oils, e.g. in Germany, Austria and France. These liquid transportation fuels are based on the use of food crops. From the viewpoint of economics, environment, land use, water use, chemical fertilizer use, etc., however, there is a strong preference for the use of woody, grassy materials as well as agricultural residues, municipal wastes and industrial wastes (e.g. black liquid) as a feedstock. Thus, the production of the synthetic transportation fuels such as biomethanol, bioethanol, DME (dimethyl-ether), FT (Fischer–Tropsch) fuel, SNG (synthetic natural gas) and hydrogen via gasification and synthesis is promising. Production of these fuels from coal and natural gas has been well commercialized e.g. by Sasol and Mobil [1]. For biomass, however, the technology has not been established mainly due to difficulty in syngas production/cleaning-up from biomass.

2. Classification of 1st and 2nd generation bio-automotive fuels

Bioethanol production has reached 38 billion liters in 2006, amounting to 3.5% of gasoline produced annually worldwide. US and Brazil have been the world's the major producers and the major consumers of bioethanol from corn and sugarcane, respectively, producing 95% of the world's total. The growth of the US market is a relatively recent trend that makes US to be the largest bioethanol producer. The most frequent use of ethanol at present is through conversion into ethyl tertiary butyl ether (ETBE) by etherification of ethanol and isobutene, the latter being a by-product of refinery processes [2]. ETBE, however, may have (like other ether-oxygenates) some disadvantages, such as potential ground water contamination.

Biodiesel production in the world has been more than 6 billion liters in 2006, of which more than 90% was produced in the EU25, mainly from rapeseed oil. Growth has been most marked in Germany where pure biodiesel enjoys a 100% fuel tax exemption. The vegetable oil is converted into methyl esters (Fatty Acid Methyl Ester or FAME). Today, methanol, derived from fossil fuel, is used for the esterification. A better option in the future would be to use biomethanol in the FAME production, or the production of Fatty Acid Ethyl Ester (FAEE) bio-ethanol instead of methanol.

The production of biogas is a third available pathway. It can be either produced in dedicated facilities from organic wastes or

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recovered from municipal solid waste landfills. The recovery of biogas is important not only as a resource, but also for avoiding the discharge of a greenhouse gas in the atmosphere. Upgraded biogas compressed at a pressure around 200 atm can be used as an engine fuel, but presently represents a niche market.

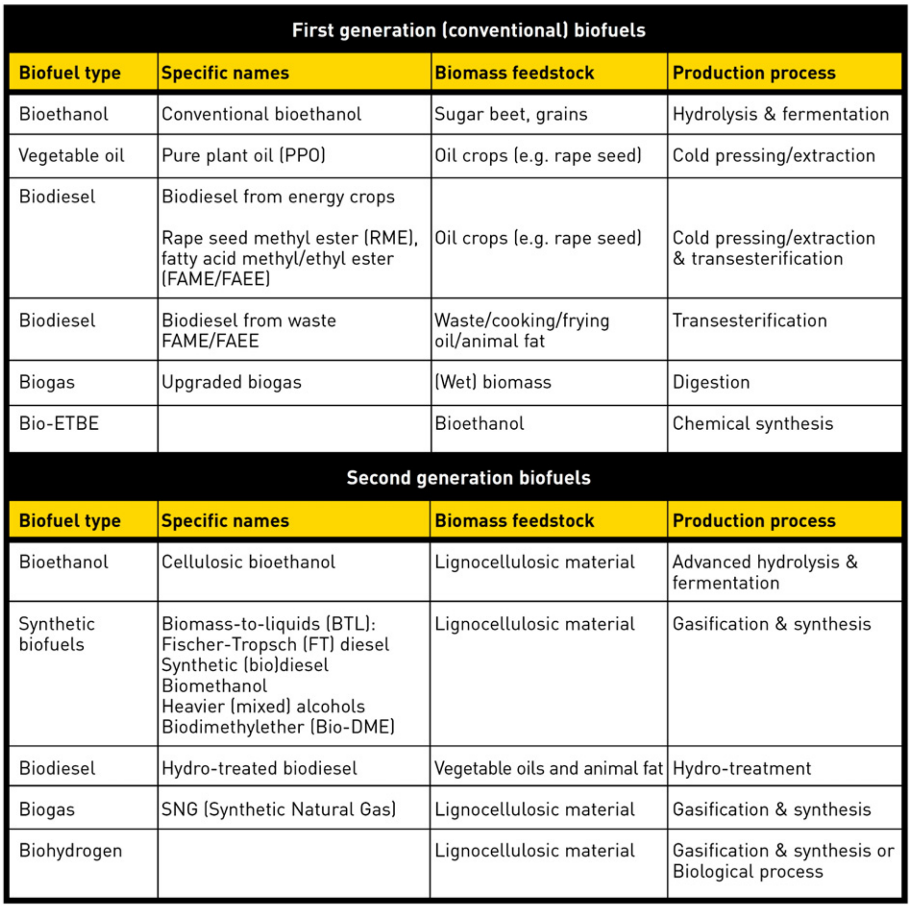
As shown in Fig. 1, the bioethanol from sugar crops, biodiesel from oil crops and biogas from organic wastes are classified as the 1st generation bio-automotive fuels. The various biomass feedstock used for producing bio-automotive fuels can be grouped into two basic categories. The first is the currently available "first-generation" feedstock, which comprises various grain and vegetable crops. These are harvested for their sugar, starch, or oil content and can be converted into liquid fuels using conventional technology. The yields from the feedstock vary considerably, with sugarcane and palm oil currently producing the most liters of fuel per hectare. The potential for the 1st generation bio-automotive fuels is particularly large in tropical countries, where high crop yields and lower costs for land and labor dominate the production cost and provide an economic advantage that is hard for countries in temperate regions to compete with.

The 2nd generation of bio-automotive fuel feedstock comprises lingocellulosic biomass mainly from forest and agricultural residues, such as tree barks, tops and branches, demolition wood, tall grasses, and crop residues, is much more abundant than food crops and can be harvested with much less interference to the food economy and much less strain on land, air and water resources. But the conversion technologies such as hydrolysis and gasification are still under development.

The hydrolysis pathway relies on advanced enzymes that can catalyze cellulose and lignocellulose into sugars and then ferment into ethanol. The process demonstration are ongoing in US, Canada and Europe. Further progress is required to bring such conversion processes to the market. This includes more efficient biochemical systems (new enzymes, yeasts), innovative fractionation and purification processes and efficient uses of co-products etc.

The gasification pathway uses high temperatures, controlled levels of oxygen, and chemical catalysts to convert biomass into synthetic fuels, including FT-diesel, DME, biomethanol, bioethanol, SNG and hydrogen. Liquid fuels, which are compatible with current market, offer the highest potential for fast introduction of bio-automotive fuel in a large scale. The preference to liquid fuels from biomass does, however, not mean that there is no place for gaseous fuels in this strategy. SNG from biomass is likely to enter bio-automotive fuel market sooner than others. The gasification pathway is here referred to as BTS (biomass to synthetic fuels including gaseous fuels), and generally requires a larger-sized facility and a larger capital investment. Unlike hydrolysis pathway, BTS pathway can also process lignin, which comprises about one-third of plant solid matter, and can thus achieve higher product yields. A big effort is being taken in Europe for BTS demonstration. Further progress has to be made to develop and improve technologies of biomass feedstock pre-treatment, syngas purification and oxygen production required by the gasification step in a more economic way to achieve better energy integration and the carbon balance.

Another possible pathway to produce 2nd generation bio-automotive fuel is pyrolysis from which a liquid fuel, bio-oil, is obtained. Bio-oil does not appear in Fig. 1 because of a number of severe problems as an automotive fuel, such as poor volatility, high viscosity, coking, corrosiveness and high water content. Bio-oils must



First generation (conventional) biofuels

Biofuel type	Specific names	Biomass feedstock	Production process
Bioethanol	Conventional bioethanol	Sugar beet, grains	Hydrolysis & fermentation
Vegetable oil	Pure plant oil (PPO)	Oil crops (e.g. rape seed)	Cold pressing/extraction
Biodiesel	Biodiesel from energy crops Rape seed methyl ester (RME), fatty acid methyl/ethyl ester (FAME/FAEE)	Oil crops (e.g. rape seed)	Cold pressing/extraction & transesterification
Biodiesel	Biodiesel from waste FAME/FAEE	Waste/cooking/frying oil/animal fat	Transesterification
Biogas	Upgraded biogas	(Wet) biomass	Digestion
Bio-ETBE		Bioethanol	Chemical synthesis

Second generation biofuels

Biofuel type	Specific names	Biomass feedstock	Production process
Bioethanol	Cellulosic bioethanol	Lignocellulosic material	Advanced hydrolysis & fermentation
Synthetic biofuels	Biomass-to-liquids (BTL): Fischer-Tropsch (FT) diesel Synthetic (bio)diesel Biomethanol Heavier (mixed) alcohols Biodimethylether (Bio-DME)	Lignocellulosic material	Gasification & synthesis
Biodiesel	Hydro-treated biodiesel	Vegetable oils and animal fat	Hydro-treatment
Biogas	SNG (Synthetic Natural Gas)	Lignocellulosic material	Gasification & synthesis
Biohydrogen		Lignocellulosic material	Gasification & synthesis or Biological process

Fig. 1. Classification of 1st and 2nd generation bio-automotive fuels (from EU Biofuels Advisory Council [2]).

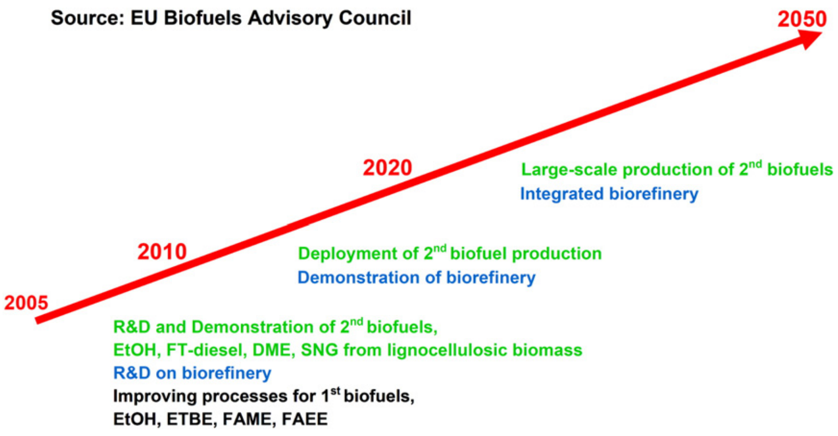

Source: EU Biofuels Advisory Council
2050
2020
Large-scale production of 2nd biofuels
Integrated biorefinery
2010
Deployment of 2nd biofuel production
Demonstration of biorefinery
2005
R&D and Demonstration of 2nd biofuels,
EtOH, FT-diesel, DME, SNG from lignocellulosic biomass
R&D on biorefinery
Improving processes for 1st biofuels,
EtOH, ETBE, FAME, FAEE

Fig. 2. Roadmap of EU bio-automotive fuel (from EU Biofuels Advisory Council [2]).

been upgraded or blended to be used in diesel engines. Upgrading of bio-oil is under research.

EU Biofuels Advisory Council made a roadmap for how to promote bio-automotive fuel production over next 40 years as seen in Fig. 2 [2]. It goes through 3 phases: R&D and demonstration on 2nd bio-automotive fuel production up to 2010; technology deployment up to 2020 after 1st commercial plant is built up around 2010; and the large scale introduction of bio-automotive fuel production integrated in bio-refinery system.

3. Syngas to bio-automotive fuels

Making H_2 and CO (syngas) from biomass is widely recognized as an important platform in the production of 2nd generation bio-automotive fuels. Apart from fuel gas or product gas of biomass gasification towards power generation, the definition of syngas emphasizes two chemical components, CO and H_2, although an unwelcome component of CH_4 resides in the gas typically by 5% to 10%. Syngas application to transportation in the form of synthetic liquid fuels has been well developed in terms of CTL (coal to liquids) based on coal, and GTL (natural gas to liquids) focusing, to a large extent, on remotely located natural gas reserves. Commercially available fossil-based technologies from syngas to bio-automotive fuels are shown in Fig. 3 as solid line arrows. Only synthesis of ethanol from syngas is under development stage.

Methanol, today, is almost exclusively produced from syngas, using a copper–zinc-based catalyst allowing the conversion of syngas to methanol at pressures of 50–100 atm and temperature of 200–300 °C. Biomass-to-methanol efficiency can be as high as 55% [3]. Several demonstration projects had been run in different parts of the world. In Japan, for example, Mitsubishi Heavy Industries is operating a pilot plant for the production of methanol from biomass. In USA, the hynol process originally developed at the Brookhaven National Laboratory was tested on a pilot scale, and was successful in converting materials such as woodchips into methanol.

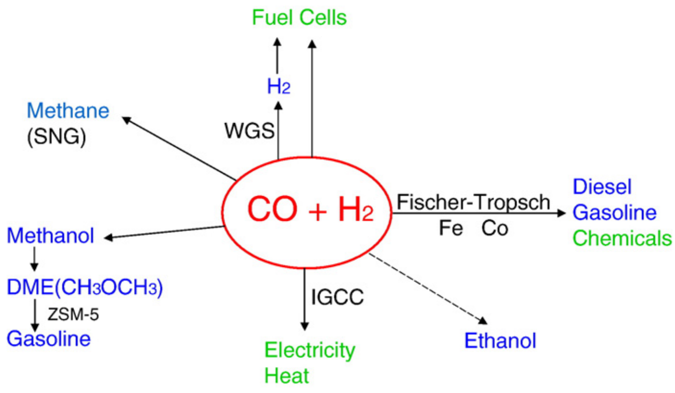


Fig. 3. Commercially available fuel products from syngas.

Gasoline production from methanol is realized with zeolite catalysts, ZSM-5, which was discovered by Mobil's Chemical by accident. This discovery later led to New Zealand MTG plant in 1985 that produce about 0.6 Mtons gasoline per year from natural gas.

DME is traditionally converted from methanol. It can easily be obtained from a special alumina catalyst reactor (310 °C and 26 atm) when DME, as the gas phase product, is removed from equilibrated mixture of methanol, DME and water. Single step production of DME from syngas is under development. DME is a colorless gas under normal condition, and turns to liquid phase under the pressure of 6.1 atm. The boiling point is −25.1 °C. It is a good substitute to liquefied petroleum gas (LPG). Its high cetane number (60) and inherent high oxygen content make it to be an attractive diesel engine fuel. DME has been used as a transportation fuel in Canada in spite of its short history.

FT diesel is a high quality diesel with cetane numbers up to 75. The fuel is absolutely S and N-free. Its aromaticity is very low, and gives rise to significantly lower emissions of HC, CO, NO_x and particles compared to standard diesel fuels. There are two FT operating modes. The high temperature (300–350 °C) process with iron-based catalysis is used for the production of gasoline and linear low molecular mass olefins. The low-temperature (200–240 °C) process with either iron or cobalt catalysts is used for the production of high molecular mass linear waxes that can be hydrocracked to diesel. FT plants are operated and are being built around world by Sasol, Shell, Chevron, Exxon etc. Three coal-based Sasol FT plants operating in South Africa have the current capacity of 7.5 Mtons product of chemicals, linear alkenes, gasoline, diesel, waxes etc. Another methane-based plant (Mossgas) produces about 1 Mtons with diesel and gasoline the main product [1].

For ethanol synthesis, commercial methanol catalysts based on Cu/Co/ZnO can be modified to also catalyze the synthesis reaction with a medium selectivity towards ethanol (<60% C2-components). A higher selectivity of 75% ethanol can be achieved with supported rhodium catalysts with $H_2/CO = 1$ at temperature around 275 °C and pressure 100 atm. It is shown that the production cost of hydrolysis-ethanol is double of the synthesis ethanol (0.85 euro/l to 0.44 euro/l) [4]. Based upon previous techno-economic studies for the production of methanol and hydrogen from biomass, Phillips [5] shows that synthesis ethanol has the possibility of being produced in a manner that is cost competitive with corn-ethanol by 2012.

4. Biomass gasification for BTS (biomass to synthetic fuels)

4.1. Gasifier design

Biomass gasifiers can been classified as air-blown, oxygen-blown or steam-blown in terms of gasification agent; as atmospheric or pressurized in terms of pressure; as slagging or non-slagging in terms of temperature; as updraft, downdraft, fluidized bed or entrained flow in terms of fluid-dynamics; as allothermal (indirect) or autothermal (direct) in terms of heat supply to endothermic gasification reactions; and as allothermal, autothermal or entrained flow in terms of application to syngas production.

In the allothermal process, the gasification heat is provided externally through a heat exchanger or the circulation of heat carrying bed material between a gasifier and a combustor. In the autothermal process, biomass is gasified directly by steam and oxygen at a temperature between 750 °C and 950 °C with help of catalyst. In entrained flow gasification, biomass is gasified by steam and oxygen at a temperature over 1250 °C without help of catalyst.

For synthesis of bio-automotive fuels, a nitrogen-free syngas can be produced by oxygen or steam blown gasifiers. Gasification with air produces a fuel gas of 4–7 MJ/Nm^3 LHV which is useless. Pure oxygen gasification gives a fuel LHV of 10–12 MJ/Nm^3, which is popular for fossil fuel-based synthetic fuel production. However, a typical oxygen plant can reach the cost of the gasification plant, and require 15% extra energy. The use of oxygen in gasification is too expensive and energy consuming for biomass-based plant that has to be built in a much smaller scale [6]. Allothermal gasification with steam instead of oxygen can provide a 12–20 MJ/Nm^3 LHV syngas.

A number of allothermal, autothermal and entrained flow gasifiers are under development and have the potential to produce a syngas suitable for bio-automotive fuel synthesis. These gasifiers have been operated in the 5 to 350 tons per day scale. The syngas properties from three types of gasifiers are listed in Table 1 as indicative values in comparison to coal-based syngas.

4.2. Allothermal gasification

A typical example of allothermal gasification is dual-bed gasifier. One bed is blown with steam to gasify biomass and to produce syngas at 700–900 °C, the other bed is blown with air to burn char to produce heat. The bed material as the heat carrier is circulated between these two beds to transfer heat from the combustion bed to the gasification bed, while separating the flue gases in the combustor from the syngas in the steam gasifier. The bed material, together with the char left over from steam gasification, is circulated to the combustion bed. Such a concept was first tested in a pilot plant with SilvaGas design developed by Battelle in the US in the eighties, which consists of two CFBs interconnected with each other [7]. In the later FERCO-Battelle design, the CFB combustor was modified to a fluidized bed combustor. On the other hand, in the Fast Internal Circulation Fluidised Bed (FICFB) process developed by the Vienna University of Technology, the CFB steam gasifier is changed to a fluidized bed instead [8]. A novel design of the fluidized bed gasifier is proposed recently by Xu etc. [9], in which, the fluidized bed is replaced by a two-stage fluidized bed to enhance thermal decomposition of tars in the upper stage of the bed. A summary of allothermal gasifiers regarding fundamental research has been reviewed by Corella [10,11].

Table 1
Indicative composition of syngas from different gasifier designs.

Syngas properties (vol%, dry)	Allo-thermal	Auto-thermal	Entrained flow	Coal, entrained flow
H_2	40	26	39	32
CO	25	20	38	55
CO_2	21	35	20	8
CH_4	10	13	0.1	0
C_2H_4	2.5	3	0	0
N_2	1.5	3	3	3
H_2/CO	1.6	1.3	1.0	0.6
LHV (MJ/m^3)	14	12	10	11

The Milena gasifier developed at ECN is similar to FERCO-Battelle design, but the CFB riser as the gasifier is allocated inside the fluidized bed combustor. The gasifier is now scaled up from lab-scale 30 kWth (in operation since 2004) to 800 kWth. The construction of the Milena pilot plant is finished in 2008 for SNG production. [12].

In the Blue-tower design developed by D.M.2 GmbH, ceramic balls of 5–10 mm diameter are used as the heat carrier to circulate from the combustor first to the steam reformer for a high temperature tar/methane reforming, then to the low temperature pyrolizer for biomass gasification.

In the MTCI design, the heat is supplied indirectly through heat transfer surfaces that are formed from the resonant section of a pulse combustor immersed within the bottom of a fluidized bed. The internal component works as both combustor and pulse-enhanced heat exchanger. A fraction of product gas is turned back to burn in the combustor.

Recently, the 12 MWth Chalmers circulating fluidized bed boiler was reconstructed by replacing the external heat exchanger with a 4 MWth steam fluidized bed gasifier for syngas production [13]. The objective of the reconstruction is to demonstrate allothermal gasification technology for the synthesis of bio-methane as the substitute to natural gas used in Gothenburg city.

The advantages of allothermal gasification are:

- No oxygen demand to obtain nitrogen-free syngas;
- Low investment costs;
- No or simple pre-treatment of biomass;
- Easy feeding of biomass;
- Suitable for biomass-based S & M scale bio-automotive fuel plant up to 200 MW;
- Avoiding problem with S-poisoning of Ni catalyst by bed material circulation between gasifier and combustor;
- Low temperature operation;
- Technology has been developed and demonstrated for heat and electricity production.

However,

- Since most operate at low pressure, they require product gas compression for downstream purification and synthesis unit operations.
- The erosion of refractory due to circulating hot solids in the gasifier can also present some potential operational difficulties.
- Tars and CH_4 reforming needs downstream catalytic upgrading.
- Ash accumulates in the gasifier.
- Syngas cleaning is a big challenge.
- Steam conversion efficiency is low [10]. The ratio of steam to biomass and energy recovery must be optimized in order to obtain high gasification efficiency.

4.3. Autothermal gasification

Single BFB or CFB is normally employed for autothermal gasification due to its scaling-up possibility for synthetic fuel production. Although the capital intensity of autothermal gasification is twice as high as allothermal gasification [5], the technology is promising when the system is pressurized to facilitate syngas cleaning and to match downstream synthesis reactor.

VTT recently started the UCG-programme (Ultra Clean Fuel Gas), and a 500 kWth pilot plant is constructed [14]. It consists of a pressurized fluidized bed, catalytic reforming, and further cleaning and conditioning. The catalytic reformer is meant to reduce hydrocarbons completely and methane by over 95%.

GTI-Carbona pressurized fluidized bed biomass gasifier has been demonstrated at commercial scale based on experience of a pilot plant, RENUGAS® 10 tons/day in Chicago 1985 to 100 tons/day in Maui, Hawaii 1994 using bagasse by Carbona [15]. It operates at a lower temperature of 1000 °C than a slagging gasifier with a pressure up to 30 atm. Carbona/UPM BTL project aims at a 250–300 MW FT plant for operation in 2012. UPM is a global forestry company and prepares to be a significant FT bio-diesel producer by developing biomass gasification and syngas cleanup.

The German institute CUTEC has recently constructed an oxygen-blown 0.4 MWth CFB gasifier connected to a catalytic reformer. Part of the gas is compressed and directed to a Fischer–Tropsch synthesis reactor.

The advantages of autothermal gasification are:

- Simple reconstruction of gasifier by switching gasification agent from air to oxygen to obtain nitrogen-free syngas
- Simple pre-treatment of biomass
- Suitable for M&L scale bio-automotive fuel plant over 200 MW
- Since most operate at high pressure, product gas compression is not needed for downstream purification and synthesis unit operations.

However,

- The erosion of refractory due to circulating hot solids in the gasifier can present some potential operational difficulties.
- Tars and CH_4 reforming is a challenge.
- High capital investment.
- An expensive and energy-consuming oxygen production plant is needed.

4.4. Entrained flow gasification

Entrained flow gasification technology has been well commercialized in large scale IGCC coal power plant [16]. In some cases even mixtures of coal and biomass have been tested successfully. The gasifiers typically operate at high temperatures over 1300 °C at which feedstock is completely converted into syngas in a few seconds with little or no methane and other hydrocarbons. The temperature can be as low as 1000–1100 °C if the biomass is used and has sufficient catalytically active components like K or Na, which is the case for e.g. straw and black liquor [17]. Entrained flow gasifier is also called slagging gasifier. The ash is melt, condenses on the relatively cold walls and ultimately forms a layer being solid close to the wall and liquid on the inner side. This slag layer serves as a protective layer for the wall. The liquid slag is removed from the bottom of the gasifier. In most cases, the gasifiers are operated under pressure (typically 20–50 bar) and with pure oxygen and with capacities in the order of several hundreds of MWth. The gasifier manufacturers are Shell, Texaco, Krupp-Uhde, Future-Energy, E-gas, MHI (Mitsubishi Heavy Industries), Hitachi and CHOREN [16].

The advantages of entrained flow gasifiers for biomass application are [18]:

- Almost 100% carbon conversion leading to high syngas production efficiency of 80%;
- Free of tars, little methane in the syngas leading to simple cleaning of inorganic impurities;
- Simple disposal of slagging ash which can be used as construction materials.

The application is limited by that:

- Biomass-based plant should have much smaller scale which does not match high capital investment of the gasification system.
- Biomass must be pre-treated into a gas or pumpable liquid or slurry at high pressure and into powder at low pressure, in order to be able to feed into the gasifier.

There are some good ideas to deal with the biomass feeding problem:

- Biomass is first converted to bio-oil via fast pyrolysis (at 500 °C) in many small plants, which is then transported to a large centralized gasification plant.
- Biomass is first converted into volatile and char via slow pyrolysis (at 500 °C). Both volatile and pulverized char can easily be injected into the gasifiers [19].
- Biomass is first turned to a brittle, easy-pulverized material via torrefaction by a mild heat treatment at 250–300 °C, which is so called bio-coal that can be treated as coal [20].

4.5. Syngas cleaning

The most expensive part of an FT complex is the production of purified syngas, which account for 60 to 70% of the total cost in the case of natural gas. With the greater complexity of gasifying coal, a coal based FT complex can cost up to 50% more than a natural gas-based operation. Other 50% more cost is expected to be added when biomass is used as feedstock [6]. This is due to the cost on biomass gasification and particularly the syngas cleaning which is the biggest share of the total cost and the biggest challenge to the BTS commercialization.

Product gas for synthesis normally has a much stricter specification on impurities than other applications such as gas engine, turbine and fuel cells [21]. Synthesis catalysts can be poisoned by NH_3, HCN, H_2S, and COS. HCl causes corrosion of catalysts. Alkaline metals and tars can be deposited on catalysts and cause poisoning of catalysts and contaminate the products. Particles (dust, soot, ash) cause fouling of the reactor. All these impurities should be removed to a concentration below 1 ppmV for an economic optimum determined by catalyst stand-time and investment in gas cleaning. A lower level of 0.1 ppmV of total sulphur and 0.01 ppmV of the halides and alkaline metals are expected.

Syngas cleanup consists of multiple operations: reforming of tars and other hydrocarbons to CO and H_2; particle and ash removal by cooling/quench; acid gas removal by scruber which also removes impurities such as particulates and ammonia along with any residual tars; CO_2 and H_2S removal by an amine unit. There has been much experience in the hot gas cleaning related to engine/turbine applications [22,23]. The wet gas cleaning is necessary for bio-automotive fuel production due to stricter requirement by synthesis reactors and lower synthesis process temperature. The wet gas cleaning (cyclone and filter, scrubbing based on chemical or physical absorption etc.) has been well commercialized for large-scale coal gasification systems [16].

The biggest challenge for allothermal and autothermal gasfications is reforming of tars/CH_4 to an acceptable low level. In addition to high temperature destruction over 1250 °C and low temperature catalytic destruction under 950 °C [24], some physical treatment are employed in FICFB plant in Gussing by biodiesel scrubbing and OLGA process with liquid oil scrubbing developed by ECN (Energy research Centre of the Netherlands) [25]. For the both cases, the removal is circulated back into the combustion part of the gasifiers.

4.6. MSU gasifier

MSU (Mid Sweden University) 150 kWth pilot-scale gasifier has been built up in 2008 for the research on synthetic fuel production as seen in Fig. 4. The gasifier was developed based allothermal concept. The gasifier consists of a BFB gasifier and a CFB combustor. The limestone bed material is used as the heat carrier to circulate between the two beds and provides heat to biomass steam gasification. The bed material with char moves from the gasifier into the combustor, where the charcoal is burned with air. The product gas from the gasifier is

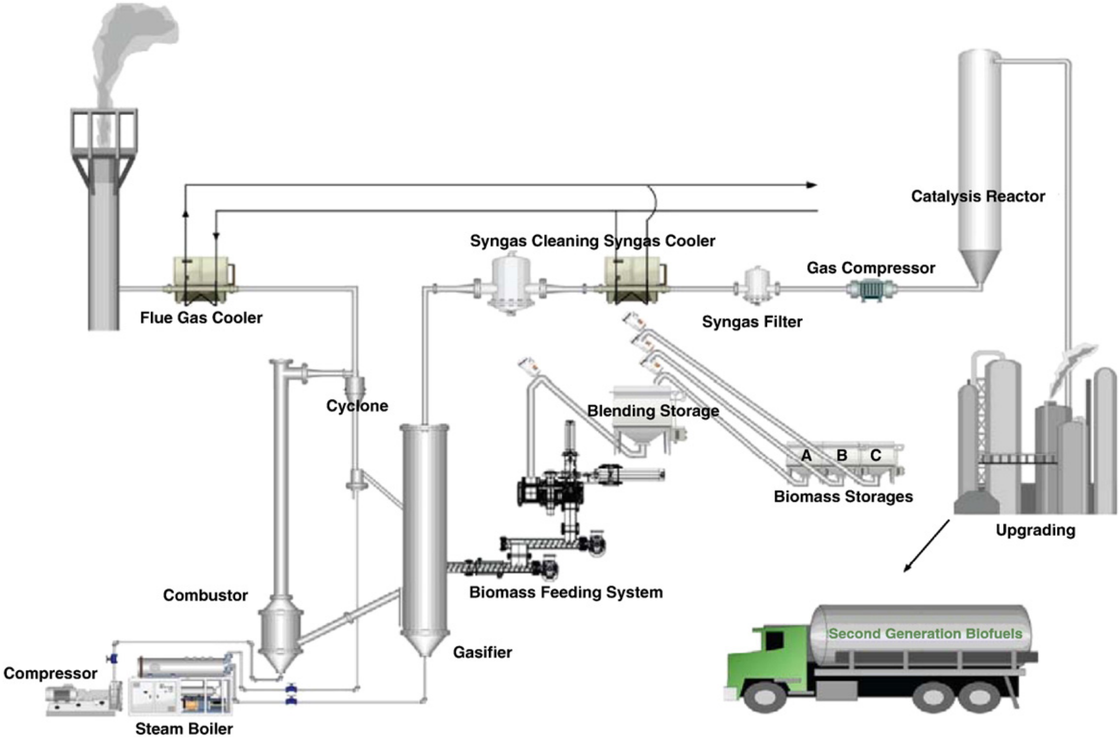


Fig. 4. MSU gasification pilot plant for BTS production.

further reformed catalytically at an elevated temperature to crack down remaining tar and methane. The syngas from the reformer is burned in a furnace at present, and is planed to be integrated to bio-automotive fuel synthesis reactors next year.

The temperature of gasification is normally held by an energy balance between the gasifier and the combustor. The low gasification temperature, the more char left over to the combustor, and the higher temperature of bed material, as a result, the gasification temperature is increased. The temperature can be controlled by bed material recirculation and electric heater surrounding the gasifier. The gasifier temperature is operated at 750 °C and the combustor temperature 900 °C.

5. BTS demonstration and cost estimation

Gussing demonstration plant in Austria, is based on indirect or allothermal gasification, which was commissioned at the end of 2001 (see Fig. 5) [8,26–28]. The plant is about 8 MWth (50 tons/day of wood chips from forest) in biomass feeding capacity, which is turned to be 2 MW electrical output and 4.5 MW district heating output. The steam blown dual bed design of CFB combustor — BFB gasifier was developed at the Vienna University of Technology in cooperation with AE Energietechnik under the name FICFB (fast internal circulating fluidized bed) since 1997 [8].

In the FICFB process, biomass is gasified in a BFB with steam at temperature 850 °C. The heat required by steam gasification is provided by a bed material as the heat carrier from the CFB combustion riser giving a product gas nearly free of nitrogen and a medium calorific fuel gas of about 13 MJ/m^3. Char is burned with air in the combustion riser at temperature over 850 °C. Tars and particles are removed from the syngas in a filter and a subsequent RME (rape-methyl-ester) scruber.

The gasifier is now used to produce SNG and FT diesel and connected to SOFC for electricity production, by joining a number of EU-FP6 projects, BIG Power, Flexgas, RENEW, Bio-SNG and AER-Gas. In RENEW project, a bypass flow of about 7 Nm^3/h syngas is compressed to 20–30 bar and converted to 0.3 kg/h FT-fuel in a slurry reactor in 2007. In AER-Gas project, the olivine bed material is replaced by sorbent CaO (calcined limestone) which performs absorption enhanced reforming (AER). Thus, a hydrogen-rich syngas (50% increased from 37%) is obtained as CO_2 is absorbed directly in the gasifier by carbonating CaO into $CaCO_3$ which will be regenerated in the combustion riser by the calcination reaction. AER can improve gasifier operation for biomass ash of low melting temperature; remove CO_2 for in situ gas conditioning; remove tars, S components, halogens etc.; reduce gasification temperature from 850 to 700 °C so that the efficiency is increased [28].

Värnamo demonstration plant is based on directly or auto-thermal gasification, which was constructed during 1991–1993, operated 1993–1999 for electricity production from biomass (see Fig. 6) [29–31]. The plant is about 18 MWth in biomass treatment capacity and has be tested successfully with wood chips, wood pellets, straw pellets and refuse derived fuel. The operating temperature of the gasifier is 850 °C and the pressure is approximately 18 bar. The gasifier is a circulating fluidized bed (CFB) and consists of the gasifier itself, cyclone and cyclone return leg. These three parts are fully refractory lined.

In the process, the dried and crushed biomass is pressurized in a lock-hopper system to a level determined by the pressure ratio of the gas turbine, and fed by screw feeders into the gasifier a few meters above the bottom. The gas produced transports the bed material, magnesite (MgO) and the remaining char to the top of the gasifier and into the cyclone. The magnesite has properties that make it highly resistant to sintering and bed agglomeration. In the cyclone, most of the solids are separated from the gas and are returned to the bottom of the gasifier through the return leg. The recirculated solids contain some char, which is burned in the bottom zone where air is introduced into the gasifier. The combustion maintains the required temperature in the gasifier. After the cyclone, the gas produced flows to a gas cooler and a hot gas filter. The gas cooler is of a fire tube design and cools the gas to a temperature 350–400 °C. After cooling, the gas enters the candle filter vessel where particulate is cleaned up.

At the moment, the Värnamo plant is rebuilt from electricity production to bio-automotive fuel, DME, methanol and FT diesel from biomass in an EU PF6 project, CHRISGAS. Thus, the gasification agent,

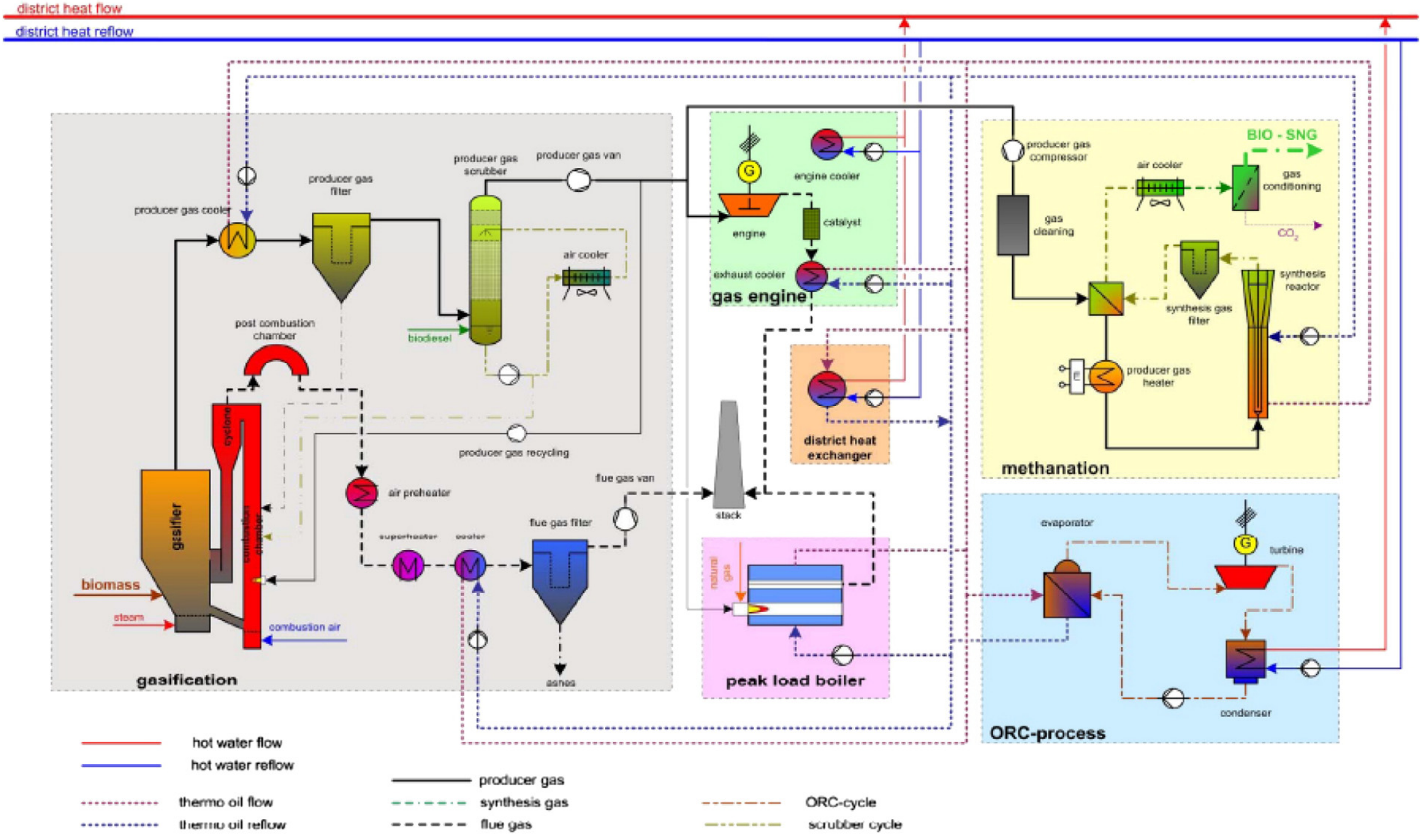


Fig. 5. Gussing gasification demonstration plant (from European Centre of Renewable Energy) [26,27].

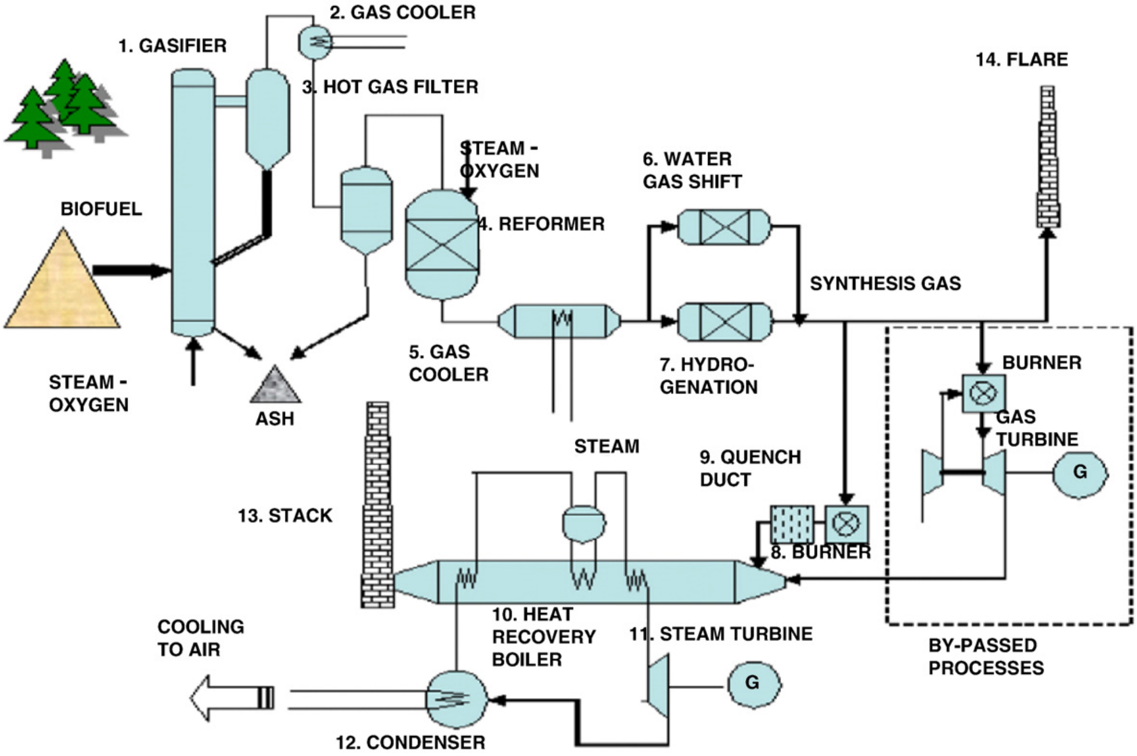


Fig. 6. Värnamo gasification demonstration plant (from VVBGC) [30,31].

air, is replaced by oxygen/steam. An oxygen blown auto-thermal reforming (ATR) component is added to crack down tar and CH_4 at 950 °C. Before ATR, a hot gas filter is installed and operated at temperature of 650 °C to remove ash particles. Downstream of ATR, a water gas shift (WGS) reactor is connected to adjust ratio of H_2/CO high enough for synthesis of bio-automotive fuels. If the lifetime of nickel based commercial catalysts is too short (due to the traces of poisoning species, such as heavy and alkali metals, H_2S, COS and SO_2), a non-catalytic partial oxidation (POX) will be chosen instead. The rebuilding of the Värnamo plant is expected to be completed in May 2009.

The gasification concept of CHOREN demonstration plant was developed based on entrained flow gasifier, which is turned to be a three steps biomass gasification of 1) biomass slow pyrolysis, 2) volatile reforming and 3) pulverized char gasification. The concept has been patented as Carbo-V® process and demonstrated in a 1 MW gasifier (alpha plant) in Freiberg, Germany since 2003 (see Fig. 7) [19,32,33]. After a short period of methanol synthesis, the unit was modified to FT synthesis. Methanol and FT hydrocarbons were produced between 2000 and 2006 in the scale of several thousand liters. The gasifier is scaled up to a 45 MW beta plant. A commercial FT unit is added to this plant using Shell's Middle Distillate Synthesis Process. The plant is built up in March 2008. Due to the simplicity of pyrolysis process, every kind of lignocellulosic biomass such as forest residues, recycle wood and to a certain extent even straw can be used as feedstock.

In the first step, biomass undergoes volatilization through partial oxidation at temperature between 400 and 500 °C. The volatile from

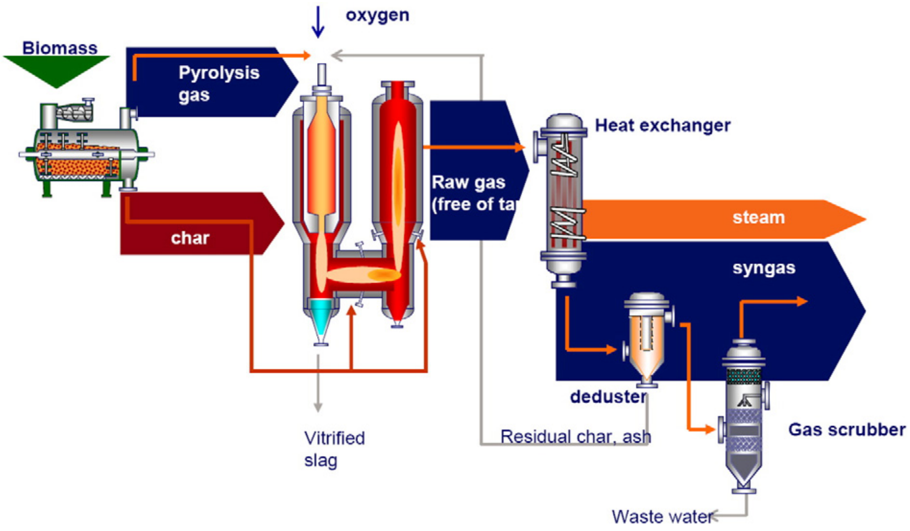


Fig. 7. Carbo-V® gasification demonstration plant (from CHOREN) [32,33].

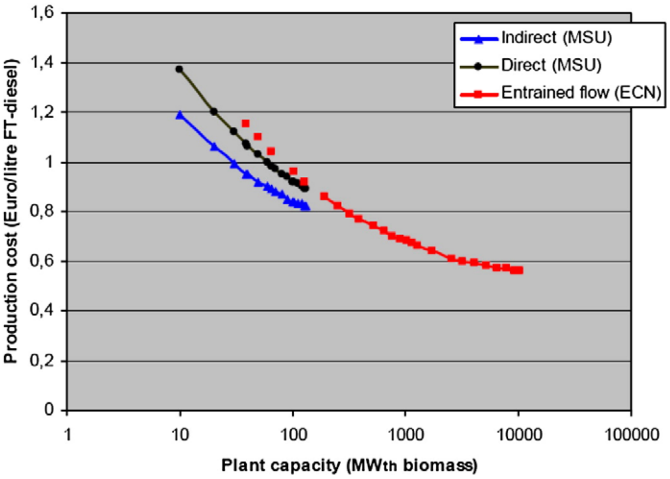


Fig. 8. FT-diesel production cost versus the plant size for different gasification technologies.

the first step is injected into an entrained flow gasifier where the volatile is heated up to 1400 °C by partial oxidation of oxygen. Tar and methane experience thermal cracking and disappear completely in the second step, followed by chemical quench as the third step from high temperature down to around 800 °C by means of endothermic gasification of the char powder injected at the downstream of the volatile gas reforming. Ash from dust removal unit is fed into the gasifier to be molten to a glasslike molten mass which is quenched in water receiving a vitrified slag. After cleaning in a scrubber to remove chlorides, sulphur compounds and trace impurities, the syngas is ready to synthesis of FT diesel.

A biomass-to-DME demonstration plant with a DME output of 1000 tons per year was constructed by Guangzhou Institute of Energy Conversion in Boluo, China, and came into test phase in April 2009 [34]. In the plant, wood chips are gasified with oxygen and steam in a fluidized bed gasifier without bed material, which produce a syngas with 1.1 H_2/CO ratio. Electricity and steam are self-supported and the total efficiency of biomass-to-DME can reach 38%.

Synthetic fuel production costs very much depending on plant scale and gasification technology as shown in Fig. 8. The cost per liter FT diesel has been calculated by ECN (Energy research Centre of the Netherlands) for entrained flow gasification [18] and by MSU for allothermal and autothermal gasifications. For larger scale plant up to 1000 MW, Entrained flow gasification shows a lower cost due to higher carbon conversion efficiency. Whereas for small scale plants under 200 MW, allothermal gasification shows a lower cost as it avoids heavy capital cost on feedstock pre-treatment and oxygen production plant, and the gasification equipments are much cheaper.

Future facilities for converting lignocellulosic feedstock into bio-automotive fuels are expected to be larger than facilities now used for the production of 1st generation bio-automotive fuels, and significant economy-of-scale advantages are expected to reduce the cost of production. However, the relatively dispersed nature of biomass resources and the high cost of transporting solid biomass will put upper limits on the future plant scale.

Existing pulp and paper industry offers unique opportunities for the production of bio-automotive fuels based on BL (black liquor) from the chemicals recovery cycle. The world production of BL is about 670 TWh/year, nothing in comparison to biomass. However, BL represents a potential energy source of 300–500 MW per mill, and is a concentrated fuel similar to character of fossil fuels. Thus, a BL automotive fuel plant can be built in medium scales larger than a biomass based plant. The feedstock logistics are simplified as it integrated in the ordinary operation of the pulp & paper plant. The BL gasification process can be easily pressurized without feedstock feeding problem. Because of the above advantages of BL, the first commercial BTS plant is expected to be built based on BL. The most successful process for black liquor gasification have been Chemrec and MTCI gasifiers [17]. 3 MW Chemrec demonstration plant in Piteå, Sweden is a dedicated entrained flow gasifier operated at about 30 bar with temperatures as low as 1000–1100 °C. This is possible due to the presence of large amount of sodium, which acts as a gas-phase catalyst in the gasifier.

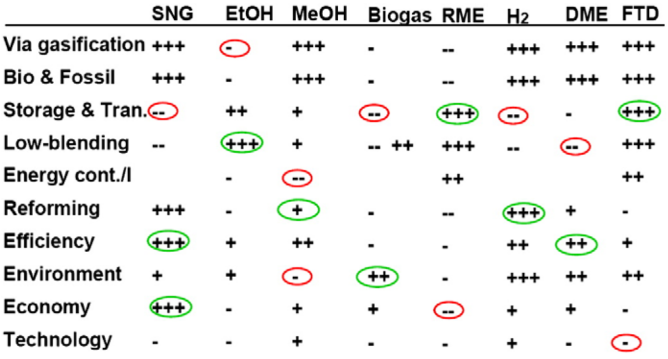
So far the integration of gasification with synthesis has not been yet demonstrated for biomass, which would be a big challenge for BTS commercialization. In the FT synthesis process, a great amount of off-gas was discharged after FT synthesis. The off-gas had approximately a half of LHV of feedstock biomass. The recycling of the off-gas to the gasifier where hydrocarbons were reformed into CO and H_2 can remarkably increase the yield of FT diesel. However, it increases power to compress the syngas and the consumption of electricity because of the increase of syngas flow rate. The cost of compressors accounted for 1/3 of the construction cost. In an improvement of the economics, the compressor section is sensitive. Therefore, a pressurized gasification that requires no compressor should be more economic for BTS.

6. Evaluation on bio-automotive fuels

From biomass gasification, a number of attractive bio-automotive fuels, SNG, EtOH (bioethanol), MeOH (biomethanol), biogas, RME (rapeseed oil biodiesel), H_2, DME and FTD (FT-diesel) can be produced. The question is left to which fuel would be the best choice to be introduced into transportation market. Considering large scale introduction into the fossil-based transportation market, biomass-based transportation fuels should be evaluated by four criteria: efficiency, economy, environmental impact and end use. These are outlined by Fig. 9 with two minus the lowest ranking and three plus the highest ranking. Biogas from anaerobic digestion of organic wastes and EtOH from cellulosic hydrolysis are included in the comparison. EtOH via gasification is not included as it has not been tested in demonstration.

It will be an advantage if

1) the fuel is produced from gasification which can take care of all different biomass material such as woody and grassy biomass, agricultural residues, municipal wastes, industrial wastes (e.g. black liquid) etc.;
2) the fuel can be produced from both biomass and fossil fuel so that the fuel production and supply may easily realized in a large scale;
3) the fuel infrastructure is already existing;
4) the fuel can be blended into present standard petrol or diesel fuel so that a new fuel market can easily be initiated;



	SNG	EtOH	MeOH	Biogas	RME	H_2	DME	FTD
Via gasification	+++	-	+++	-	--	+++	+++	+++
Bio & Fossil	+++	-	+++	-	--	+++	+++	+++
Storage & Tran.	--	++	+	--	+++	--	-	+++
Low-blending	--	+++	+	-- ++	+++	--	--	+++
Energy cont./l		-	--		++			++
Reforming	+++	-	+	-	--	+++	+	-
Efficiency	+++	+	++	-	-	++	++	+
Environment	+	+	-	++	-	+++	++	++
Economy	+++	-	+	+	--	+	+	-
Technology	-	-	+	-	-	+	-	-

Fig. 9. Evaluation of bioautomotive fuels for transportation.

5) the fuel energy density is high;
6) the fuel can easily be used in fuel cell which gives the highest power-train efficiency;
7) the fuel well-to-wheel efficiency is high;
8) production and use of the fuel do not give a high load on environment;
9) the fuel is cheap;
10) the technology has been well developed.

Ethanol is a perfect additive into petrol to increase octane number and to reduce emission of CO and particles. But, ethanol is presently produced from sugar/starch crops.

Methanol is produced from gasification that gives a fairly high efficiency compared to ethanol. But the energy content is the lowest among the liquid fuels.

Cold start at low temperature has been a serious problem for alcohol-fuelled Otto engines. Alcohols could be used in diesel engines on the condition that some kind of ignition aid is used. Alcohols are not miscible with diesel fuel.

Biogas does not have a fuel infrastructure. But the technology is an effective tool to take care of waste water, MSW etc.

RME is a good diesel fuel and is miscible with diesel. But it is produced from agricultural activity which lead to high cost.

H_2 is the best fuel to fuel cell. But the use is limited by fuel infrastructure associated to hydrogen storage and transportation. The distribution of liquid requires little energy (about 1% loss). But for gaseous hydrogen, 20% energy is lost to the operation of compressors and pipeline transportation.

SNG has a production efficiency as high as 65%. The plant can be realized in medium scale of about 100 MW. In the case where the pipeline is available, it can be fed to power station as well as to transportation vehicles.

DME, as an excellent diesel fuel, can easily be produced from gasification which makes the fuel has the highest well-to-wheel efficiency. However, DME is a gaseous fuel which can not mix with standard diesel. The production efficiency can be 60%.

FTD is a high quality diesel fuel, and miscible with standard diesel in any fraction. But, much development work has to be done before commercialization in order to obtain a reliable and cost-effective biomass gasification system. FT diesel efficiency is 35–45%.

Comparing the cases for DME and FTD, the difference lies in the fuel production efficiency. In the DME production process, the easy separation of the gaseous DME-product and recycling of liquid methanol makes the conversion more complete so that the yield is about 5% higher than methanol as the end product, and of course much more higher than FTD. In the FT-fuel production process, the hydrocarbon synthesis is more exothermal than the methanol or DME synthesis, which leads to a higher energy loss. And also, FT synthesis produces more water, which accounts for about 25% of total energy losses due to condensation of FT reaction water. Another reason is that a wide range of hydrocarbons, as well as oxygenated products such as alcohols and aldehydes are produced from FT process.

7. Conclusion

The 1st generation bio-automotive fuels such as bioethanol and biodiesel from food crops will remain as favourable fuels in the tropical developing countries. The 2nd generation bio-automotive synthetic fuels (BTS) such as methanol, ethanol, DME, FT-diesel, SNG and hydrogen produced via gasification from forest and agricultural biomass residues are on the way to a breakthrough in the transport markets of industrial countries especially for those countries with a strong forest industry. The technology of producing BTS is well established based on fossil fuels. For biomass, a great effort is being taken to demonstrate 3 gasification technologies, allothermal, autothermal and entrained-flow gasifications, worldwide, especially in European Union. Entrained-flow and autothermal gasification technologies are suitable for M&L scale bio-automotive fuel production plants, while allothermal gasification is suitable for S&M scale plants.

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